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FE BASED TRANSFORMING SINGLE CRYSTALS

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Abstract

We report on the stress-strain response of Co-Ni-Al with a two-phase microstructure which displayed an unusual decrease in critical stress (84%) with strain or thermal cycling accompanied with an improved recoverability of pseudoelastic and shape memory strains. The repeated deformation also produced a decrease in stress hysteresis and a reduction in residual strain making this material rather attractive for ferromagnetic shape memory applications.

1. Introduction

Newly developed transforming materials such as Co-Ni-Al exhibit a narrow thermal hysteresis (less than 30°C), and ferromagnetic shape memory (FSM) behavior [1-2]. The ferromagnetic shape memory refers to motion of magnetic domains in the martensitic state under applied magnetic fields. The potential of this class of materials for actuation and sensing has generated considerable interest. However, their mechanical response is not fully understood. Recently, considerable focus has been devoted to FSM alloys such as Ni-Mn-Ga [3-5], which exhibit low ductility, as well as Fe-Pd [6, 7] and Fe-Pt [8] which show smaller shape changes. The inherent brittleness and the high cost of constituent elements in all of these alloys make the Co-Ni-Al with its moderate ductility and lower cost an attractive alternative. Furthermore, it is well known that shape memory properties degrade with cycling in conventional shape memory alloys. The present work is undertaken to develop a better understanding of the cyclic response of Co-Ni-Al.

We report for the first time the transient cyclic stress-strain response leading to stabilized behavior. A noteworthy difference between the present and the previous heat treatments was that the heat treatment was conducted at 1200° C for 24 hours resulting in a two-phase microstructure consisting of the β (ordered B2) and γ (ductile fcc) phases, rather than a single-phase microstructure more typical of other studies on Co-Ni-Al alloys [9-13].

The basis for shape memory behavior is the reversible thermoelastic martensitic transformation. Although the term thermoelastic implies completely reversible deformation, researchers have discovered irreversibilities following thermal and mechanical cycling [14-15]. Because these materials will be used in cyclic applications such as actuation, the degradation of recoverable deformation poses serious limitations. A number of investigations have shown a reduction in critical stress [16-17], a change in stress hysteresis [15,17,19], and an alteration of transformation temperatures [16] upon repeated transformation cycles in conventional shape memory alloys. The changes in critical stress have been confined to less than 30% in most cases. The underlying factor in these changes is the accumulated unrecovered (residual) strain during thermal and mechanical cycling and internal dissipation [15] producing large increases in hysteresis. Materials and conditions that circumvent these known trends require further study and elaboration, motivating a closer look at Co-Ni-Al alloys.

We present data showing an unusually large decrease in critical stress resulting from cycling of up to 84%, which far exceeds previously reported levels in the literature for any shape memory materials. Our results demonstrate a critical stress-temperature relationship that is highly sensitive to the deformation history, but ultimately reaches stabilized stress levels. We explain this behavior using current understanding between internal stresses arising from defects and cyclic shape memory behavior.

Figure 1 shows the stress-strain response for compression cycles at -22°C. These loading temperatures were selected to represent two extreme cases of pseudoelasticity; the 22°C loading temperature is near the $A \rightarrow M$ temperature. The critical stress for each cycle is shown by the small arrows and subsequent cycles showed a decrease in apparent modulus and therefore the procedure described was repeated for each sample and each cycle. Pseudoelastic recovery is defined as the magnitude of recovered strain upon unloading. The strain caused by the shape memory effect (SME strain) is the recovered strain at zero stress during heating. These two strains are illustrated in Figure 1. By the third cycle, the critical stress decreases by approximately 98 MPa, or 84%, at –22 ° C and by 465 MPa, or 70%, at 100 ° C, respectively. Notice the difference between the stress-strain response of the material during the first and the third cycles at both temperatures.

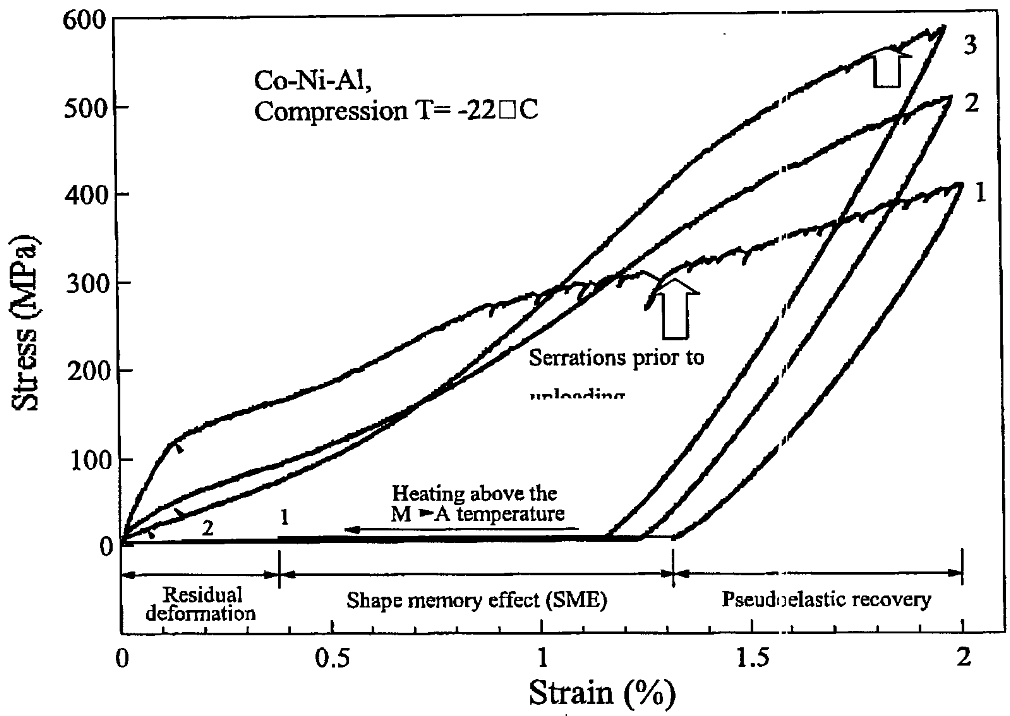

Figure 1 Cyclic stress-strain results shown for two extreme temperatures demonstrating the improved recoverability of pseudoelastic and SME strains with cycling. By the third cycle the critical stress decreased in by 98 MPa, or 84%, at -22°C. The small arrows indicate the critical stress at the onset of transformation. The large vertical arrows indicate the stress hysteresis. Stress drops (serrations) exist in the curves prior to unloading and are distinguished by large arrows in (a). The frequency of the serrations decreased with cycling.

Common to both test temperatures, noticeable serrations (i.e. stress drops) exist in the first cycle stress-strain curves prior to unloading as indicate in Figure 1. Serrations in the curve are more distinct at -22°C as compared to 100°C. These serrations could result from the formation of different martensite variants within different grains or from the interaction of the transforming interface with the second phase constituent. It is apparent from Figure 1 that cycling decreases the frequency of the serrations as well as their magnitude.

Stabilization of the stress-strain behavior was observed during cycling experiments. A sample was considered stabilized when the residual deformation saturates for a given applied strain upon cycling. Concomitant with stabilization, a distinct decrease in the frequency of stress drops prior to unloading is noticeable in Figure 1. In Figure 1, the first cycle showed 0.38% residual deformation, which progressively decreased in subsequent cycles until it became zero after the third cycle. Therefore, the sample was considered stabilized after the third cycle. In Figure 1, the first cycle showed 0.42% residual deformation, and the third cycle showed a negligible change as compared to the second. Therefore, although residual deformation remained, the stress-strain response of the material was considered to be stable after the third cycle. A sample that showed only improved recoverability of pseudoelastic or SME strains was defined as moderately stabilized.

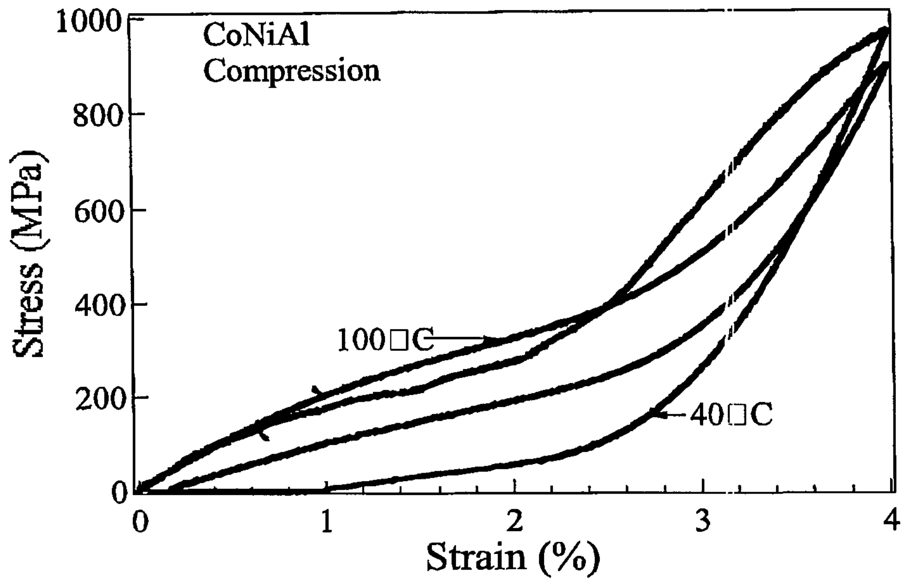

Figure 2 The pseudoelastic response of a stabilized specimen at 40°C (third cycle) and 100°C (fifth cycle). The recoverable strain (including elastic recovery) is as high as 4% at 100°C.

Another example of the stabilized stress-strain response is considered Figure 2 in which pseudoelastic behavior was observed. The specimen was subjected to five loading cycles in which the isothermal test temperature was increased for successive cycles. Only the third and the fifth cycles are shown, which were conducted at 40°C and 100°C, respectively. The first two loading cycles at room temperature resulted in 0.51% residual deformation. The third and fifth cycles recovered the total deformation (4%). For the pre-stabilized specimen the stress hysteresis decreased with increasing test temperature (comparing the 40°C and 100°C results). Compared to the virgin specimen in Figure 1, the stabilization drastically improved the pseudoelastic recovery

4. Discussion of Results

In previous studies the decrease in critical stress has been associated with the generation of dislocations and residual martensite after few transformation cycles [16,18-21]. These changes are typically less than 25% in NiTi and Cu-based shape memory alloys, and are therefore considerably smaller than the remarkable changes approaching 84% in this study. Dislocations readily form at transformation fronts depending on the slip resistance of these domains and the magnitude of the transformation shear strain. These dislocations prevent reverse transformation of a fraction of the martensite plates, which leads to the presence of residual martensite. The subsequent stress fields surrounding the residual martensite and the associated dislocation arrangements act to preferentially orient the nucleating variants of martensite to the externally applied stress, thus facilitating the subsequent transformation [21] from austenite to martensite. The residual martensite also acts as a new nucleation site [21]. Under pseudoelastic cycling, the development of these internal stress fields assists the driving force for the forward transformation, thereby contributing to the decreases in critical stress levels. It is evident, by the drastic decrease in critical stress shown in Figure 1, that internal stress fields and enhanced nucleation sites have a more pronounced effect in Co-Ni-Al compared to other well known shape memory alloys. Finally, the secondary (ductile fcc) phase clearly provides an additional source of internal stresses, which is apparently unique to Co-Ni-Al with this heat treatment.

The experimental results demonstrated that the recoverable strain increased with cycles reaching a 'stabilized' level. In successive cycles, we postulate that the density of dislocations and the volume fraction of residual martensite accrued during the transformation both decrease causing the reduction in residual strain. Residual strain remains if unrecoverable deformation resulting from the slip in austenite and martensite domains and the pre-existing residual martensite persists. The presence of preferential martensite nucleation and lowered resistance from the secondary phase reduces the plastic relaxation mechanisms thus lowering the residual strain. We postulate that stabilization leads to full recovery near the $M \rightarrow A$ transformation temperature, shown in Figure 1, because deformation is mainly associated with the movement of twin boundaries, rearrangement of twin boundaries, and elastic deformation of martensite variants. We note that the residual deformation after stabilization at 100° C (102° C above the $(A \rightarrow M)$ transformation temperature), shown in Figure 1, remains because slip occurs in austenite domains near the M_d temperature at such high stresses (Sehitoglu et al. [22]).

The mechanisms for the substantial decrease in critical stress combined with the stress-temperature diagram and cyclic pseudoelastic effects demonstrate that the Co-Ni-Al system can be tailored to produce excellent shape memory and ferromagnetic shape memory characteristics. The results from this work also establish a large temperature range (145°C) over which shape memory and pseudoleasticity can occur in these materials. This broad range of temperature increases the potential utility of these materials.

5. Conclusions

The following conclusions are drawn from this work:

- A significant decrease in critical stress as compared to other shape memory alloys was observed under repeated transformation cycling. The low critical stress levels near the martensite start temperature sets the stage for ferromagnetic shape memory applications for this class of alloys. The possibility of using these materials as actuators and sensors is being explored.

- Repeated cycling produced preferential martensite variants and an internal stress pattern that continually decreases the unrecoverable deformation with cycling. Repeated transformations eventually saturate the residual strain, approaching a stabilized condition

- The material exhibited a considerably larger pseudoelastic window of 145°C as compared to traditional shape memory materials. Combined with the maximum pseudoelastic strains approaching 4% this alloy has potential benefits compared to other shape memory materials.

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